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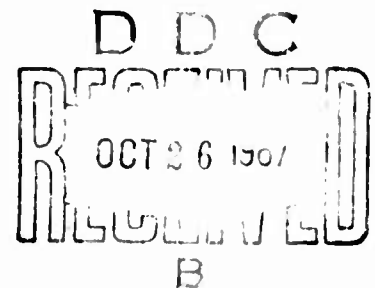
# NUCLEAR WEAPON BURST PARAMETERS GOVERNING URBAN FIRE VULNERABILITY

by

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#### ADMINISTRATIVE INFORMATION

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## SPECIAL SUMMARY

## The Problem

The need exists to provide background information on nuclear-explosion phenomenology and effects relevant to urban fire vulnerability, to identify the nuclear weapon burst parameters that influence this vulnerability, and to determine the relative importance of each parameter.

The state-of-the-art review reported herein was performed as part of a larger study of urban fire-vulnerability parameters sponsored by the Office of Civil Defense (OCD) and reported in Ref. 1. Separate publication of this information was suggested by OCD in order to make it more widely available to those with interests in urban fire vulnerability to nuclear attack.

The OCD Research Task Order describes the overall study as follows: "Perform a comprehensive identification of the parameters pertinent to an assessment of the vulnerability of urban areas to fire from nuclear weapon attacks and other causes in the trans-and post-attack periods and an evaluation of their relative importance. The investigation should include, but not be restricted to, parameters associated with: level of ignition energy; atmospheric transmission; weather and climate; kindling fuel characteristics and distribution; fire development from thermal-radiation-set ignition points and other causes such as blast and accidents; building geometry and arrangement; city plan and topography."

## The Findings

The weapon burst parameters governing thermal effects from nuclear weapon explosions are reviewed as part of the OCD program for assessing urban vulnerability to fire from nuclear bursts. The most important burst parameters are weapon yield, burst height, distance from target, and number of bursts. Spatial, temporal, and spectral characteristics of fireball development and thermal output are discussed as functions of these parameters. Peak blast overpressure as a function of yield, burst altitude and distance from ground zero is briefly discussed in relation to blast-caused secondary ignitions. The material presented will be useful for approximate calculations of weapon effects in analysis of urban fire vulnerability and other problems.

The scaling laws and other relationships presented in this report are expected to apply with reasonable accuracy to a nuclear-weapon explosion of any yield and height of burst. The variation with range of radiant exposure and peak overpressure are discussed briefly and convenient rules are given for purposes of estimation, including a simple model of atmospheric attenuation of thermal radiation for clear, cloudless conditions.

## ABSTRACT

The weapon burst parameters governing thermal effects from nuclear weapon explosions are reviewed as part of the OCD program for assessing urban vulnerability to fire from nuclear bursts. The most important burst parameters are weapon yield, burst height, distance from target, and number of bursts. Spatial, temporal, and spectral characteristics of fireball development and thermal output are discussed as functions of these parameters. Peak blast overpressure as a function of yield, burst altitude and distance from ground zero is briefly discussed in relation to blast-caused secondary ignitions. The material presented will be useful for approximate calculations of weapon effects in analysis of urban fire vulnerability and other problems.

## SUMMARY PAGE

### The Problem

Estimation or assessment of the fire vulnerability of urban targets to nuclear attack requires information on the characteristics of the thermal-radiation pulse emitted by a nuclear explosion and of accompanying airblast as functions of various burst parameters. This information is contained in many references and should be made more readily available in one up-to-date report for researchers with interests in the urban-fire-vulnerability problem and related problems.

### The Findings

A state-of-the-art survey was made of the literature on nuclear-explosion phenomenology and effects that are relevant to urban fire vulnerability, and the resulting information was evaluated to determine the burst parameters that are significant to such vulnerability. It is concluded that the most important burst parameters affecting radiant exposure and other effects of urban fire vulnerability are, in approximate order of importance:

1. Distance from weapon burst to target.
2. Total weapon yield.
3. Burst altitude, both above sea level and above local terrain.
4. Number of bursts (contributing to the total yield).

Formulas are presented by means of which total-energy, spatial, temporal, and spectral characteristics of the thermal pulse can be calculated as functions of these parameters, for any yield and burst height. The important subject of atmospheric transmission of thermal radiation is discussed briefly, as is the variation of blast-wave peak overpressures with range, yield, and burst height.

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## SECTION 1

### INTRODUCTION

#### 1.1 STATEMENT OF THE TASK

The state-of-the-art review reported herein was performed as part of a larger study of urban fire-vulnerability parameters sponsored by the Office of Civil Defense (OCD) and reported in Ref. 1. Separate publication of this information was suggested by OCD in order to make it more widely available to those with interests in urban fire vulnerability to nuclear attack.

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#### 1.2 PURPOSE AND SCOPE OF REPORT

The purpose of this report is to provide background information on nuclear-explosion phenomenology and effects relevant to urban fire vulnerability, to identify the nuclear weapon burst parameters that influence this vulnerability, and to determine the relative importance of each parameter.

The scaling laws and other relationships presented in this report are expected to apply with reasonable accuracy to a nuclear-weapon explosion of any yield and height of burst. The variation with range of radiant exposure and peak overpressure are discussed briefly and convenient rules are given for purposes of estimation, including a simple model of atmospheric attenuation of thermal radiation for clear, cloudless conditions.



### 1.3 APPROACH

The report begins by considering (in Section 2) the effects of weapon yield and height of burst on fireball development and thermal-energy emission. Expressions for the various characteristics are given for surface bursts and for above-surface bursts from sea-level to outside the atmosphere.

The effect of range from burst point to target is then discussed (in Section 3). A convenient model for atmospheric transmittance of thermal radiation as a function of range and burst height is given. The effect of range and burst height on peak overpressures is presented graphically.

Finally (in Section 4), the effect of distributing a given total weapon yield among a number of warheads, as compared to a single weapon of equivalent total yield, is considered. Expressions are derived for total blast- and thermal-affected areas as functions of the number of warheads.

## SECTION 2

### EFFECTS OF WEAPON YIELD AND BURST ALTITUDE

#### 2.1 INITIAL EXPLOSION PHENOMENA\*

The initial phase of a nuclear explosion proceeds in a manner independent of the surrounding environment. Within a fraction of a microsecond after detonation, the fission products, bomb casing, and other debris have been raised to a temperature of several tens of millions of degrees Kelvin. Before the bomb vapors have had time to expand appreciably (within a microsecond), a considerable fraction (~70%) of the total energy present appears as thermal radiation in the form of soft X-rays of several keV average energy, depending on the temperature of the weapon. The remainder is primarily contained in the kinetic energy of the vapors, which expand (until they collide with the medium surrounding the weapon) at a velocity of several hundred miles per second.

#### 2.2 LOW ALTITUDE DETONATIONS (< 15 mi)

##### 2.2.1 Air Bursts

2.2.1.1 Fireball Development. In an air burst at sea level or low altitude, the primary thermal X-rays are absorbed within a few feet of the bomb, giving rise to extremely high temperatures within the initial fireball. The energy is immediately reradiated and again absorbed in surrounding cold air; hence, the fireball grows at high velocity as the radiant energy diffuses outward.

Since the mean free path of the thermal radiation in air at these temperatures is large compared to the fireball dimensions, energy is rapidly distributed within the fireball, and the temperature throughout remains quite uniform as the fireball grows and cools. The mass of hot gases in the region behind the radiation front is therefore referred to as the isothermal sphere.

The spectral distribution of radiation from the fireball can be approximated by the spectrum of a black body at the surface temperature of the fireball. However, only relatively low-energy (visible and near-visible) radiation, a small fraction of the total, can escape from the immediate vicinity of the isothermal sphere at early times; essentially all the shorter-wavelength (higher-energy) photons are reabsorbed by the surrounding air.

\* Ref. 2, pp. 26, 68-69

A sudden rise in pressure is produced at the radiation front. As the fireball cools and the propagation velocity of the radiation front decreases, this pressure discontinuity develops into a strong shock front, which separates from the isothermal sphere. This event ("hydrodynamic separation") occurs in low-altitude explosions when the temperature of the fireball has fallen to around 300,000°C (about 0.1 msec after detonation for a 20-KT explosion).\*

After hydrodynamic separation, the apparent surface of the fireball is the location of the shock front, since the air heated to incandescence by its passage is opaque to the radiations of the isothermal sphere. The temperature of the shock-heated air is considerably less than that of the isothermal sphere, however, so that the apparent surface temperature and observed rate of energy emission of the fireball drop off rapidly. The temperature of the isothermal sphere continues to fall, but remains higher than that of the surrounding shock front. The opacity of the shock front prevails until its temperature has fallen to around 1800°C. As the shocked air approaches this temperature, it emits and absorbs less radiation and gradually becomes transparent to the radiations of the isothermal sphere. The time at which the isothermal sphere can again be seen through the faintly incandescent shock front is known as "breakaway" (about 15 msec after a 20-KT detonation).

Following breakaway, the thermal emission and apparent surface temperature again increase as the unmasking of the isothermal sphere continues. A maximum is reached of around 7000-8000°C (for small yields), when most of the radiation falls in the visible region and the fireball has nearly reached its maximum size. At later times the rate of emission falls off as the fireball continues to cool by radiation, expansion and entrapment of outside cold air.

Thus, the rate of thermal emission and apparent surface temperature of the fireball in a low-altitude explosion are characterized by an extremely rapid rise to a maximum, followed by a rapid fall to a minimum and a slower rise to a second maximum. This behavior is illustrated in Fig. 1.

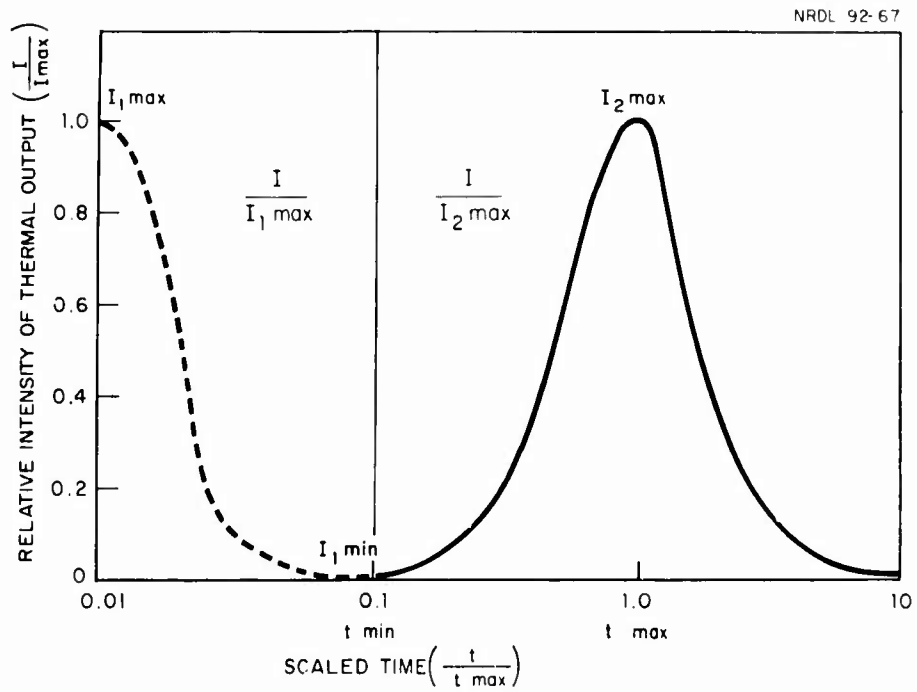
2.2.1.2 Effects of Yield and Atmospheric Density on Fireball Characteristics. In a 20-KT explosion the thermal minimum occurs about 11 milleseconds after detonation ( $t_{\min}$ ), and the second thermal maximum at about 140 msec ( $t_{\max}$ ).\*\* These times are roughly proportional to the square root of weapon yield. An approximate scaling law for  $t_{\max}$  which has been widely used is:\*\*

$$t_{\max} \approx 0.032 W^{\frac{1}{3}} \text{ sec} \quad (1)$$

for W in kilotons.

\* Ref. 2, p. 71.

\*\*Ref. 2, p. 76.



**Figure 1 Nuclear Weapon Thermal Pulse Shape<sup>3</sup>**

According to Rogers and Miller,\* this expression predicts times about 30% too short for a kiloton yield and about 30% too long for yields of several megatons, with even greater errors at larger yields. If Eq. 1 is corrected to agree with Rogers and Miller it becomes:

$$t_{\max} \approx 0.044 W^{0.43} \text{ sec} \quad (2)$$

This equation is presumably more accurate at all yields than Eq. 1.

In spite of its limited accuracy, however, Eq. 1 has the advantage of convenience in that, if it is converted to megaton units, it becomes:

$$\begin{aligned} t_{\max} &\approx 1.01 W^{\frac{1}{2}} \text{ sec} \\ &\approx W^{\frac{1}{2}} \end{aligned} \quad (3)$$

Within the range of 1 KT to several MT, this equation is good to  $\pm 30\%$ .

At altitudes above sea level,  $t_{\max}$  is also roughly proportional to the square root of atmospheric density,<sup>5,6</sup> so that Eq. 3 becomes:

$$t_{\max} \approx (W \rho / \rho_0)^{\frac{1}{2}} \text{ sec} \quad (4)$$

where  $\rho / \rho_0$  is the ratio of burst-point to sea-level atmospheric density. Since  $\rho / \rho_0$  is about  $10^{-2}$  at 20 miles altitude, the thermal pulse from an explosion at that altitude is about an order of magnitude shorter than that at sea level.

Atmospheric density up to about 80 miles is approximated well by the formula\*\*

$$\rho / \rho_0 \approx e^{-h/4.3} \quad (5)$$

where  $h$  is altitude above sea level in miles. This can be written:

\* Ref. 4, p. A-22.

\*\* Ref. 2, p. 531

$$\begin{aligned}\rho/\rho_0 &\approx 10^{-h/9.9} \\ &\approx 10^{-h/10}\end{aligned}\tag{6}$$

which provides the convenient rule that atmospheric density changes by roughly a factor of 10 for every 10-mile change in altitude.

The fireball radius at  $t_{\max}$  can be similarly scaled with yield. For near-sea-level air bursts, the radius is given approximately (within  $\pm 30\%$ ) by:\*

$$R_{\max} \approx 180 W^{0.4} \text{ ft}\tag{7}$$

for  $W$  in Kt.

Taking into account both yield and density variations, Martin and Holton<sup>1</sup> give the following equations for  $t_{\max}$  and  $R_{\max}$  as functions of yield and burst altitude:

$$t_{\max} = 0.82 W^{0.42} e^{-0.09h} \text{ sec}\tag{8}$$

$$R_{\max} = 0.41 W^{0.35} e^{0.0465h} \text{ miles}\tag{9}$$

where  $W$  is in megatons and burst altitude  $h$  is in miles. These equations are probably quite accurate below 20 or 30 miles, but may be unreliable at greater altitudes. On substituting Eq. 5 in the exponential terms involving  $h$ , it can be seen that Eqs. 8 and 9 assume that  $t_{\max}$  varies as  $(\rho/\rho_0)^{0.4}$  and  $R_{\max}$  varies as  $(\rho/\rho_0)^{0.2}$ .

**2.2.1.3 Thermal Output and Fireball Temperature.** In the low-altitude range, the shape of the thermal pulse (normalized so that  $t_{\max} = 1$ ), the fireball temperatures at  $t_{\min}$  and  $t_{\max}$ , and the overall energy partition between thermal radiation and blast are independent, or slowly varying functions, of yield and burst altitude. Approximately 30% to 40% of the weapon yield is converted into thermal radiant energy, most of it in the visible and near-infrared spectrum, and about 50% into blast energy. The spectral distribution of the thermal energy is not quite that of a

\* Ref. 2, pp. 10, 77-78.

black body, being somewhat depleted in the ultraviolet and infrared. However, it may be approximated fairly well by a Planck spectrum.\* For typical fireball temperatures this predicts about 10% of the energy in the UV, 40% in the visible, and 50% in the near IR regions. The first thermal pulse, emitted at high temperature, is very brief and represents less than 1% of the total thermal energy, whereas the second pulse contains 99% of the energy and is radiated over a much longer time at a lower temperature. Of the total thermal energy, approximately 20%, 50%, and 80% have been emitted by times  $t_{\max}$ ,  $2 t_{\max}$ , and  $10 t_{\max}$  respectively, as shown in Fig. 2. Only that fraction of the energy emitted before  $10 t_{\max}$  can be considered effective in starting fires, since the later radiation is emitted too slowly to be effective.

Observations of high-yield explosions have shown that fireball temperature at the second thermal maximum decreases slightly as yield increases. An approximate function describing this variation can be derived from knowledge of the thermal-pulse shape and fireball size and the Stefan-Boltzmann law for the power emitted by a black body,

$$P = \sigma AT^4 \quad (10)$$

where  $T$  is the temperature of the body,  $A$  is the emitting area, and  $\sigma$  is the Stefan-Boltzmann constant. The power temperature of a fireball is thus defined by:

$$T_p = \left[ \frac{P}{\sigma A} \right]^{\frac{1}{4}} \quad (11)$$

The total effective thermal energy emitted by the fireball is the time integral of its thermal power,

$$fW = \int_0^{10 t_{\max}} P dt \quad (12)$$

which can be written

$$\begin{aligned} fW &= P_{\max} t_{\max} \int_0^{10} \frac{P}{P_{\max}} \frac{dt}{t_{\max}} \\ &= k P_{\max} t_{\max} \end{aligned} \quad (13)$$

\* Ref. 2, pp. 350-353.

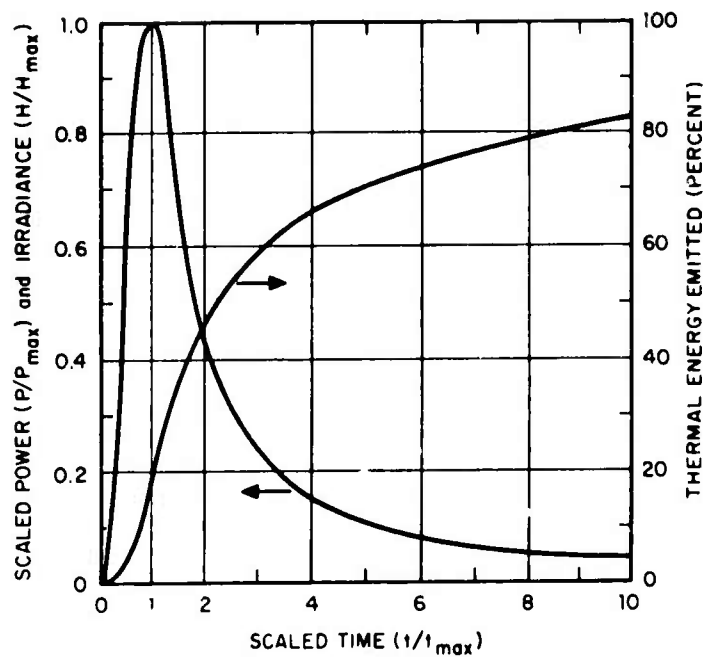


Figure 2 Scaled Fireball Power and Fraction of Thermal Energy Vs Scaled Time<sup>2</sup>



where  $P_{\max}$  is power at  $t_{\max}$  and  $f$  is the fraction of weapon yield emitted as effective thermal radiation. The integral has been evaluated<sup>8</sup> for the weapon pulse given in Glasstone (see Fig. 2), and  $k$  was found to be approximately 2.07. Solving for  $P_{\max}$ , we obtain

$$P_{\max} \approx \frac{fW}{2.07 t_{\max}} \quad (14)$$

Substituting the expressions for  $t_{\max}$ ,  $R_{\max}$ , and  $P_{\max}$  from Eqs. 8, 9 and 14 into Eq. 11, and assuming an effective thermal partition  $f$  of  $\frac{1}{3}$ , gives the fireball temperature at second thermal maximum:

$$T_{\max} = \left[ \frac{fW/k t_{\max}}{\sigma 4 \pi R_{\max}^2} \right]^{\frac{1}{4}}$$

$$\approx \left[ \frac{0.33 W}{2.07(0.82 W^{0.42} e^{-0.09h}) \sigma 4 \pi (0.41 W^{0.35} e^{0.0465h})^2} \right]^{\frac{1}{4}} \quad (15)$$

$$\approx 7200 W^{-0.03} \text{ } ^\circ\text{K}$$

where  $W$  is in megatons. For a yield of 20 KT, Eq. 15 predicts a  $T_{\max}$  of  $8100^\circ\text{K}$ , which is in good agreement with the value of  $7700^\circ\text{C}$  (or  $\sim 8000^\circ\text{K}$ ) given in Glasstone.\*

## 2.2.2 Surface Bursts

**2.2.2.1 Fireball Development and Characteristics.** When a nuclear explosion occurs on or near the surface of the earth, the explosion phenomena are affected in several ways. About half of the weapon debris and primary thermal X-rays are initially directed downward. When the weapon debris strikes the ground, most of it is reflected upward; while the thin layer of surface material which absorbs the primary thermal radiation is raised to very high temperatures and pressures and quickly blows off upward. A crater of considerable size (about 0.1-mile radius from a 1-MT surface burst on dry soil)\*\* is produced by displacement and

\* Ref. 2, p. 76.

\*\* Ref. 2, p. 293.

vaporization of surface material, and a strong shock wave is induced in the ground. The major fraction of the weapon energy, however, is still contained in the thermal pulse and blast wave.

The reflected shock waves soon merge with the primary fireball shock wave. As this strengthened shock front travels out from the fireball, it remains opaque longer than the shock front from an airburst of the same yield; thus,  $t_{\min}$  and  $t_{\max}$  are shifted to later times, and the fireball radius at  $t_{\max}$  is increased. In fact, the fireball from a surface burst of a weapon of yield  $W$  develops approximately as that of an airburst of yield  $2W$ . Equations 8 and 9 thus become approximately<sup>7</sup>

$$t'_{\max} \approx t(2W) = 1.1 W^{0.42} e^{-0.09h} \text{ sec} \quad (16)$$

$$R'_{\max} \approx R(2W) = 0.5 W^{0.35} e^{0.05h} \text{ miles.} \quad (17)$$

**2.2.2.2 Thermal Output and Fireball Temperature.** Because of the roughly hemispherical shape of the fireball, as well as the considerable amount of dirt and debris thrown up near the burst point, less thermal energy is received at a given distance from a surface burst than from an airburst of the same yield. Glasstone\* estimates the effective thermal partition of a surface burst as one-half to three-fourths that of an air burst, with  $f$  tending toward the larger value as yield increases and distance decreases. Martin and Holton<sup>7</sup> take a partition halfway between these values, i.e.,  $f \approx 5/8 \times 1/3 \approx 0.21$ . Note that this applies only to targets along the ground; from the air, where a larger area of the fireball can be seen, radiant exposures will be greater.

We may estimate the fireball power temperature at  $t_{\max}$  in a manner similar to that for an air burst. There is some evidence that the shape of the thermal pulse shown in Fig. 2, and thus the value of the integral in Eq. 13, is different for air and surface bursts. The variation seems to be relatively minor, however; therefore the indicated value of  $k$ , 2.07, will be accepted as approximately correct for surface bursts. Assuming the thermal partition to be 0.21, the radiating area (of the visible portion of the fireball) to be  $2\pi R^2$ , and substituting from Eqs. 16 and 17, we obtain

\* Ref. 2, pp. 363, 366.

$$T'_{\max} \approx \left[ \frac{0.21 W}{2.07(1.1 W^{0.42} e^{-0.09h}) \sigma 2 \pi (0.5 W^{0.35} e^{0.05h})^2} \right]^{\frac{1}{4}}$$

$$\approx 6300 W^{-0.03} \text{ } ^\circ\text{K} \quad (18)$$

Thus, the peak temperature of a surface burst may be about 10% less than that of an air burst of the same yield. Less confidence can be placed on this estimate, however, than on the corresponding air-burst estimate, because of greater uncertainties in the values of  $t_{\max}$ ,  $R_{\max}$ ,  $f$  and  $k$  used. Some measurements indicate considerably lower values of  $T_{\max}$  for surface bursts.<sup>3</sup>

Near-surface explosions in which the fireball intersects the surface or is distorted by reflected blast energy will exhibit characteristics intermediate between those of air and contact-surface bursts. The limiting altitude above which there will be negligible interaction between the fireball and ground can be assumed to be approximately equal to  $R_{\max}$  for an air burst, given by Eq. 9.

### 2.3 HIGH-ALTITUDE DETONATIONS<sup>6</sup> (15 - 50 mi)

Below a critical altitude which depends on yield, the pulse shape previously described for low-altitude detonations is reasonably accurate. Above this altitude, the shock front develops later and less strongly, and the thermal minimum is less pronounced as the shock front becomes transparent at higher temperatures. With increasing altitude, the fraction of yield appearing as blast is progressively reduced. A larger fraction of the thermal energy is emitted before breakaway (~ 12% for a multimegaton weapon at 30 mi), the energy emitted during the second maximum is correspondingly smaller, and the pulse is increasingly curtailed after  $t_{\max}$ . Eventually, the thermal minimum and second maximum disappear completely, and the energy is radiated in a single rapid pulse of effective duration  $\tau$ , where  $\tau \approx t_{\max}$ , as given by Eq. 8.

The critical altitude is about 20 miles for a 100-KT yield and 30 miles for 100 MT. Thermal yield may be taken as  $\frac{1}{3}$  to  $\frac{1}{2}$  the total yield over the altitude range of 15 to 50 miles. The average fireball radiating temperature is probably not greatly different from that of a low-altitude burst; however, the UV and IR portions of the thermal output spectrum may be somewhat enhanced.\*

\* Ref. 2, p. 80.

## 2.4 VERY HIGH-ALTITUDE DETONATIONS<sup>2,6,9</sup> (> 50 mi)

At burst altitudes of 50 mi or so the atmosphere can no longer be assumed isotropic, since the mean free path of the primary thermal X-rays (and thus the radius of the initial fireball) is now some tens of miles, and atmospheric density varies by several orders of magnitude over this altitude range. Because of the density gradient, the spherical fireball becomes spheroidal, prolate above and oblate below. At even greater burst altitudes the distortion will be extreme: only those X-rays emitted downward will be absorbed, producing a pancake-shaped region of excitation in the denser atmosphere below the burst, while those emitted upward will escape absorption completely. The thermal radiation at the ground from such a burst will then consist of two main components: (1) a brief flash of a few microseconds duration, the visible and near-visible tail of the high-temperature bomb vapor spectrum, followed by (2) a pulse of longer duration emitted by the excited region of the atmosphere.

A considerable difference in thermal yield is to be expected between the two above-mentioned degrees of fireball distortion, which may be termed upper-atmospheric and extra-atmospheric, respectively. In the case of upper-atmospheric bursts, in which most of the primary X-radiation is still absorbed in a fireball region, the thermal efficiency  $f$  is roughly the same as that found at lower altitudes, i.e., about one-third (other characteristics are also similar to those of high-altitude bursts, described in 2.3). In extra-atmospheric bursts, on the other hand, half or more of the primary X-rays escape without significant atmospheric interaction, while the density of the excited layer is so low that re-emission of the absorbed energy may be too slow to be thermally effective. (Note that here is a case where a parameter of weapon design, yield/mass ratio, can have a considerable influence on "fireball" behavior, since the altitude and density of the excited layer, and therefore its rate of re-emission of energy, are dependent on the initial bomb temperature.) The other component of the thermal pulse, the thermal tail of the primary radiation spectrum, represents an extremely small fraction of the total weapon energy.

The transition altitude between upper-atmospheric and extra-atmospheric bursts has been estimated variously to be from around 50 mi (Miller and Passell,<sup>9</sup> for a bomb temperature of  $10^7$  K or  $\sim 1$  keV) to around 70 mi (Glasstone,<sup>2</sup> p. 323). In this regard it is worth noting that the Teak shot, an explosion in the megaton range at an altitude of  $\sim 50$  mi, produced a definite though distorted fireball and a thermal efficiency characteristic of upper-atmospheric detonations.\*

\* Ref. 2, pp. 50-52, 367.

## SECTION 3

### EFFECTS OF RANGE FROM BURST POINT TO TARGET

#### 3.1 EFFECTIVE BURST-POINT LOCATION

Because of the finite size of the fireball, the distance from its surface to a target will be somewhat less than the distance from the burst point to the target. This difference may be important when calculating atmospheric transmission for large-yield weapons. From geometrical considerations, it can be estimated<sup>10</sup> (when  $r >$  several fireball radii) that  $r_{\text{eff}} \approx r - 0.6 R_{\text{max}}$ , where  $r_{\text{eff}}$  is the average distance from the target to the surface of the fireball,  $r$  is the distance to the center of the fireball, and  $R_{\text{max}}$  is given by Eq. 9 or 17.

Similarly, in estimating the effective elevation angle of the fireball, the apparent center of the hemispherical fireball of a surface burst is located a distance of  $\sim 0.4 R_{\text{max}}$  above the ground.<sup>10</sup> The apparent center of an airburst fireball is, of course, coincident with the actual center.

Soon after detonation, the highly buoyant fireball is accelerated upward, reaching a maximum velocity of several hundred feet per second, so that its altitude increases somewhat during the thermal pulse. This variation may require modification of the effective altitude for surface bursts; whether the effect will be significant for other burst heights depends on weapon yield and ambient density. The effective burst-point location for calculation of blast effects is identical with the actual burst point.

#### 3.2 RADIANT EXPOSURE AS A FUNCTION OF RANGE

In the absence of atmospheric attenuation, the intensity of thermal radiation from a weapon fireball falls off as  $r^{-2}$ . Significant atmospheric attenuation will require addition of a transmittance factor  $T$ , which will be in general a complex function of range, wavelength, and atmospheric conditions. The thermal energy (direct and scattered) intercepted by a normally oriented unit area is then

$$Q = \frac{f W T}{4 \pi r^2} \quad (19)$$

If  $W$  is expressed in kilotons,  $r$  in miles, and  $Q$  in  $\text{cal}/\text{cm}^2$ , and  $i$  is assumed to be  $\frac{1}{3}$ , this becomes conveniently

$$Q = 1.02 \frac{WT}{r^2} \approx \frac{WT}{r^2} . \quad (20)$$

Although atmospheric transmittance is not a burst parameter in the sense used earlier, a brief discussion of it will be included here for convenience. The subject is discussed in much greater detail in Refs. 1 and 10. Gibbons<sup>10</sup> has found that a simple exponential attenuation, using the attenuation coefficients given by Elterman<sup>11</sup> for a wavelength of  $0.65\mu$ , gives an adequate fit to atmospheric transmission measurements for the actual nuclear weapon fireball spectrum, as well as to solar radiation data. Elterman's transmission term is of the form

$$T = e^{-\tau(h) \sec \theta} \quad (21)$$

where  $\tau(h)$  is optical thickness for vertical transmission from a given altitude  $h$  to sea level, and  $\theta$  is the zenith angle of the fireball ( $\sec \theta = r/h$ ). Table 1 gives Elterman's values of  $\tau$  for  $0.65\mu$  and several burst heights, as modified by Gibbons for a sea-level visibility of 12 mi. Fig. 3 is a plot of transmittance vs slant range for these burst heights.

Table 1

Optical Thickness  $\tau(h)$  as a  
Function of Burst Altitude  $h^*$

<u><math>h</math> (mi)</u>	<u><math>\tau</math> (h)</u>
0.25	0.0310
1	0.0952
2	0.1239
3	0.1341
5	0.1426
10	0.1531
20	0.1662
30	0.1680

\*From Elterman<sup>11</sup> and Gibbons<sup>10</sup>

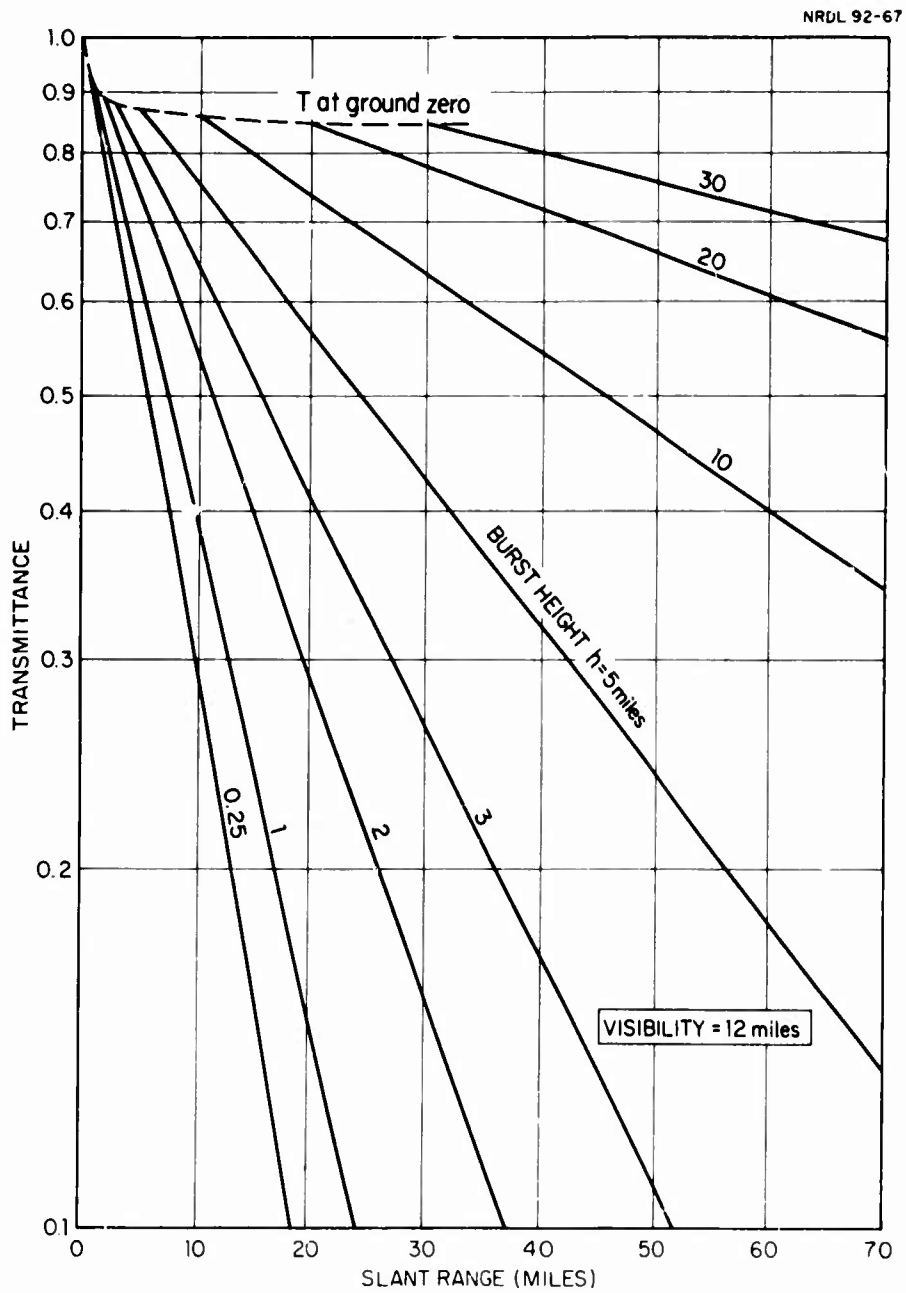


Figure 3 Transmittance Vs Slant Range for Several Burst Heights

The foregoing estimates of transmittance, it should be emphasized, are for a "clear" standard atmosphere (visibility = 12 mi) and cloudless skies. Other meteorological conditions can produce wide variations in transmittance, and the above-cited references should be consulted for greater coverage of the subject.

### 3.3 PEAK OVERPRESSURE AS A FUNCTION OF RANGE

The blast wave from a nuclear explosion can be an important cause of secondary ignitions, in addition to the primary thermally-caused ignitions.<sup>1</sup> However, the manner in which pressure, density, and velocity of the air immediately behind the shock front fall off as the front propagates out from the burst point, is rather complex even for a free-air burst. When the explosion occurs near the ground, a reflected shock wave is produced that may interact with the incident shock to complicate matters further. Since the primary interest of this study is in thermal effects, the subject of blast is not considered here in depth. The reader is referred to Glasstone<sup>2</sup> for a more complete coverage.

Figure 4 has been taken from Glasstone\* to illustrate the variation of peak overpressure on the ground as a function of distance from ground zero and burst height for a 1-KT explosion (assuming a homogeneous sea-level atmosphere at standard temperature and pressure, and near-ideal surface conditions). Note that the distance from ground zero for any given overpressure contour passes through a pronounced maximum at a certain burst height. This is an optimum height of burst that maximizes the range from ground zero at which a particular overpressure is felt; conversely, for a given range, an optimum burst height exists that will maximize the overpressure received. Similar curves can be drawn for peak dynamic pressure, defined as  $q = \frac{1}{2} \rho u^2$ , where  $\rho$  and  $u$  are respectively air density and wind velocity immediately behind the shock front.

The ordinate and abscissa of Fig. 4 scale as the cube root of the yield; that is,

$$\frac{h_2}{h_1} = \frac{D_2}{D_1} = \left( \frac{W_2}{W_1} \right)^{\frac{1}{3}} \quad (22)$$

The corresponding peak-overpressure curves for a 1-MT explosion, for example, can be obtained by simply multiplying the scales of Fig. 4 by 10. This scaling law has been found to apply well for explosions into the megaton range. However, it must be emphasized that the curves were derived from assumptions of a homogeneous standard sea-level atmosphere

\* Ref. 2, Fig. 3.67b, p. 139.



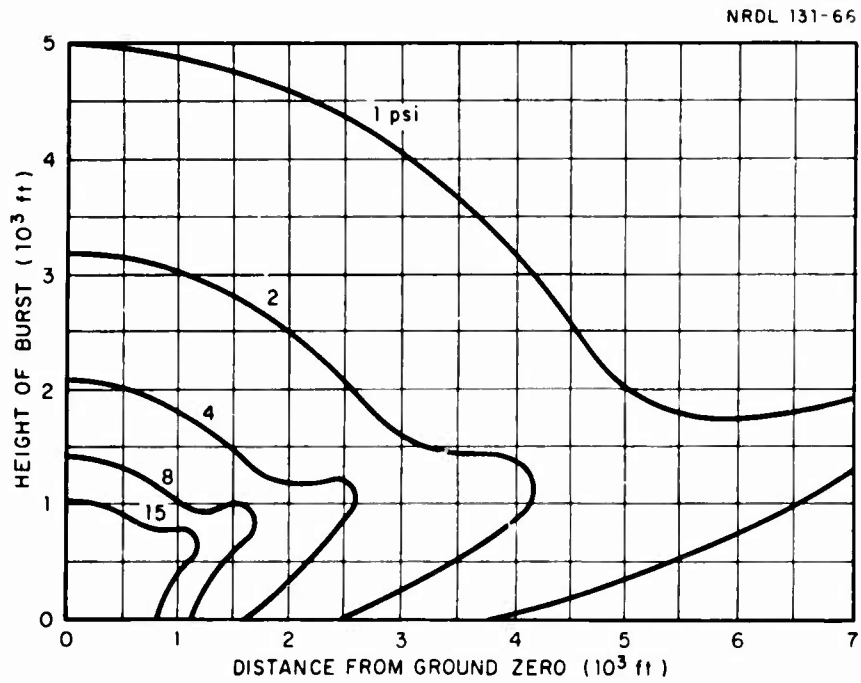


Figure 4 Peak Overpressure on the Ground for a 1-KT Burst

and near-ideal surface conditions. The first assumption is violated if the burst altitude and the target elevation differ by more than a few thousand feet, as they generally do in airbursts of large-yield weapons. Therefore, these curves should be considered only as indicative of the actual overpressures received from large-yield air bursts.

## SECTION 4

### EFFECTS OF MULTIPLE-WEAPON ATTACKS

#### 4.1 GENERAL CONSIDERATIONS

It is quite possible that in a nuclear-attack situation, several weapons may be detonated near certain U. S. urban targets, either simultaneously or consecutively. Reasons for the use of more than a single weapon include:

1. Payload limitations of delivery vehicles may require more than one weapon to accomplish destruction of a large target area.
2. Increased probability of at least one weapon on target, in the face of limited weapon-system reliability and accuracy and possible defensive countermeasures.
3. Possibly greater effectiveness of several small weapons compared with that of a single large weapon of equivalent total yield.

Only the last reason is discussed here, though certain of its conclusions apply to any multiweapon attack.

#### 4.2 EFFECT OF MULTIPLE WARHEADS ON BLAST AREA

Consider a simultaneous attack involving  $n$  warheads, each of yield  $W/n$ , delivered in salvo by a single missile. If the warheads are properly dispersed and detonated simultaneously (say, within a time  $t \approx t_{\max}$ ), their thermal pulses and blast waves will reinforce at points on the ground between their respective ground zeros. In effect, the total energy yield  $W$  is distributed more uniformly by several explosions than by a single equivalent explosion, and while destruction below the center of the burst pattern is somewhat lessened, destruction some distance away from the center is increased.

Even if the explosions are not simultaneous, or the individual ground zeros are so widely separated that no significant interaction occurs, the total destructive area may be increased under certain circumstances by use of multiple explosions. For example, if  $r(W)$  is the ground radius of a given overpressure contour as a function of yield, and  $A(W)$  is the area enclosed, then (from Eq. 22):

$$\frac{r(W/n)}{r(W)} = n^{-\frac{1}{3}}$$

$$\frac{A(W/n)}{A(W)} = n^{-\frac{2}{3}}$$

$$\frac{n A(W/n)}{A(W)} = n^{\frac{1}{3}} \quad (23)$$

For  $n = 4$  the total area of blast destruction is 60% larger than the area for an equivalent-yield single weapon.

#### 4.3 EFFECT OF MULTIPLE WARHEADS ON THERMAL AREA

A similar analysis can be performed for thermal damage. Experimental measurements<sup>12</sup> of the variation with yield of radiant exposures required for ignition of various materials showed that, for yields greater than  $\sim 100$  KT, the ignition energy  $Q_1$  was proportional to about the one-fourth power of yield for a number of typical fabrics, household materials, and paper products. Solving Eq. 20 for  $r$ ,

$$r \approx \left( \frac{WT}{Q} \right)^{\frac{1}{2}}$$

and substituting  $Q_1 = k W^{\frac{1}{4}}$  for  $Q$ , we find that the ignition radius

$$\begin{aligned} r_i &\approx \left( \frac{WT}{kW^{\frac{1}{4}}} \right)^{\frac{1}{2}} \\ &\approx k' W^{3/8}, \end{aligned} \quad (24)$$

where  $k$  and  $k'$  are proportionality constants. Thus the distance at which a given material can be ignited by a weapon pulse, disregarding changes in atmospheric attenuation, is proportional to roughly the one-third power of yield. Addition of an exponential transmission term will cause ignition radii to scale even more slowly with yield.

In the absence of atmospheric attenuation, the ratio of the total area within the non-overlapping ignition radii of  $n$  weapons, each of yield  $W/n$ , to the corresponding area for a single weapon of yield  $W$  is

$$\begin{aligned}\frac{n A(W/n)}{A(W)} &= \frac{n r^2(W/n)}{r^2(W)} \\ &= n \cdot n^{-\frac{3}{4}} \\ &= n^{\frac{1}{4}}\end{aligned}\tag{25}$$

For  $n = 4$ , the total area of primary ignitions is 40% larger than the area for a single weapon of equivalent yield. Moderate or severe atmospheric attenuation will increase the difference.

The above discussion assumes that weapon yield is linearly proportional to mass, so that total yield from a given delivered mass is independent of the number of warheads. If smaller weapons are less efficient in terms of yield/mass ratio than larger ones, then the conclusions of the previous analysis may be partially invalid as far as the effectiveness of a given missile payload is concerned.

## SECTION 5

### SUMMARY

The foregoing discussion has provided a number of functional relationships describing the variations of thermal and blast effects with changes in yield, burst altitude, range from weapon to target, number of weapons, and some other minor parameters. From these relationships some conclusions about the relative importance of these parameters can be made; for example, both radiant exposure and peak overpressure are inversely proportional to the second or greater power of range, but vary about linearly with total yield. The following ranking of the parameters, in decreasing order of importance, seems to apply to most cases:

1. Range from weapon burst-point to target.
2. Total yield.
3. Burst altitude.
4. Number of weapons (total yield fixed).

Exceptional conditions might change this ranking; e.g., when the explosion occurs very near the ground, say within one fireball radius, the characteristics of the explosion change rapidly with small changes in altitude. At extremely high altitudes, on the other hand, the most important determinant of the thermal efficiency of a weapon may be its initial temperature, which is not listed above. Finally, when atmospheric attenuation of thermal radiation is extremely severe, the area of thermal damage may be relatively insensitive to changes in weapon yield but strongly dependent on changes in the number of weapons.

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